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Synthesis, aggregation and responsivity of block copolymers containing organic arsenicals

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Block copolymers containing an organic arsenical (AsAm) have been synthesised by aqueous SET-LRP. The block copolymers are pH and thermoresponsive, forming nanoparticles in aqueous solution. Under reductive conditions the particles are stabilised through the formation of As-As bonds and stability can be tuned as a function of the AsAm monomer feed.

Living systems crosslink (bio)macromolecules in order to stabilise intra- and intermolecular interactions, supporting complex tertiary and quaternary structures and self assembled (bio)macromolecular complexes. Such biochemical processes have inspired the development of a chemical platform to control the properties and function of polymers through crosslinking. Crosslinking synthetic linear polymers not only alters physical properties such as glass transition temperature, it has been exploited to create architectures beyond one dimensional linear structures such as single chain nanoparticles,^{1, 2} star/branched polymers,^{3, 4} and nanogels.⁵ In particular, responsive materials that utilise reversible covalent bond formation that can be uncrosslinked on demand by specific environmental triggers are attractive targets for drug delivery, sustainability and chemical sensors.⁶ In a biological context, boronate esters have been demonstrated by Sumerlin *et al.* as a pH and sugar responsive cross-linker to form hydrogels,^{7, 8} with self-healing properties in acidic environment, and self-assembled particles that dissemble in presence of sugars.⁹⁻¹¹ Other types of dynamic cross-linking such as hydrazones^{12, 13} and disulfides^{14, 15} are reported in the literature for intracellular drug delivery in response to endosomal pH and redox environment.

Arsenic is an interesting candidate for dynamic cross-linking, due to its interchangeable oxidation states each with distinct chemical reactivity. For example, pentavalent arsenic (As(V)) will not form covalent bonds with thiols, preferring to undergo single electron transfer reduction. Trivalent arsenic (As(III)) can

be formed from the reduction of As(V) by two equivalents of thiol and in this oxidation state arsenic has a high affinity for thiols, readily forming covalent As-S bonds, which is markedly enhanced for dithiol reagents.¹⁶ The affinity for mono- and dithiols has been exploited for post-polymerisation modification and protein/peptide-polymer conjugation of As-functional polymer scaffolds.^{17, 18} Under stronger reducing conditions, As(V) can be directly reduced to As(I), which has been reported to proceed with reductive coupling to form As_n homocycles comprised of As-As bonds.¹⁹ The As-As bonds are weak but have been exploited in synthesis for the preparation of salvarsan²⁰ and as a source of monomer for 'ring-collapsed radical alternating copolymerisation' to form poly(vinylene arsines).²¹⁻²⁵

Until recently, the polymerisation of As-functional monomers by chain-growth polymerisation was only reported by free radical polymerisation.²⁶⁻³⁰ The advent of reversible deactivation radical polymerisation (RDRP) techniques such as reversible addition-fragmentation chain-transfer (RAFT),³¹ atom transfer radical polymerisation (ATRP)^{32, 33} and single electron transfer living radical polymerisation (SET-LRP)³⁴ enables exquisite control of chain-end functionality which has been harnessed for the synthesis of well-defined (multi)block copolymers.^{35, 36} In previous work, a protected As-functional monomer, prepared in a two-step synthesis from *p*-arsanilic acid, was employed to prepare As-functional homo- and copolymers by RAFT.¹⁷ In order to access the interesting reactivity of the pendant As-functional groups, the resulting polymers require an additional post-polymerisation processing step to afford deprotection. It would be beneficial to develop a method through which an As-functional monomer could be incorporated into polymers without the need for the additional protection (monomer) - deprotection (polymer) steps.

Herein we report the synthesis of block copolymers containing an As(V)-functional monomer (AsAm) by aqueous SET-LRP. At elevated temperatures As(V)-functional nanoparticles are formed which, for the first time, are stabilised by crosslinking through the reductive coupling of As(V) to give As(I)_n. The

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Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See

stability of the resulting particles as a function of the AsAm monomer feed is also investigated in aqueous and model

Table 1. As-functional block copolymers synthesised by aqueous SET-LRP. ^1H NMR in D_2O . SEC in DMF.

		First Block				Final Polymer			
Entry	Structures	Con.	$M_{n,th}$ (g mol^{-1})	$M_{n,SEC}$ (g mol^{-1})	\bar{D}	Con.	$M_{n,th}$ (g mol^{-1})	$M_{n,SEC}$ (g mol^{-1})	\bar{D}
	Control								
P1	PEGA ₂₀ - <i>b</i> -NIPAm ₈₀	> 99%	9800	11800	1.07	98%	20000	25400	1.27
P2	(PEGA ₁₇ - <i>S</i> -AsAm ₃)- <i>b</i> -NIPAm ₈₀	> 99%	9200	11100	1.51	> 99%	19400	25100	1.41
P3	(PEGA ₁₅ - <i>S</i> -AsAm ₅)- <i>b</i> -NIPAm ₈₀	> 99%	8800	16500	1.29	> 99%	19000	37500	1.81
P4	PEGA ₂₀ - <i>b</i> -(NIPAm ₇₅ - <i>S</i> -AsAm ₅)	> 99%	9800	7900	1.13	> 99%	20700	20000	1.49
P5	PEGA ₂₀ - <i>b</i> -(NIPAm ₇₀ - <i>S</i> -AsAm ₁₀)	> 99%	9800	10100	1.16	> 99%	21500	26000	1.19
P6	PEGA ₂₀ - <i>b</i> -(NIPAm ₆₅ - <i>S</i> -AsAm ₁₅)	> 99%	9800	9200	1.18	> 99%	22200	21000	1.42
P7	PEGA ₂₀ - <i>b</i> -(NIPAm ₆₀ - <i>S</i> -AsAm ₂₀)	> 99%	9800	9200	1.22	> 99%	22900	25600	1.57

Poly(ethylene glycol) methyl ether acrylate (PEGA, $M_n = 480 \text{ g mol}^{-1}$) and *N*-isopropylacrylamide (NIPAm) are hydrophilic monomers that have been successfully polymerised by aqueous SET-LRP previously. Therefore, PEGA was selected as the corona-forming block and NIPAm, with its ability to undergo phase transition at elevated temperatures (LCST = 32 °C), was selected as the core-forming block. For optimal chain extension and block efficiency, the PEGA blocks ($DP_{n,th} = 20$) were synthesised first then chain extended with NIPAm ($DP_{n,th} = 80$) via one-pot, sequential chain extension in accordance with previous work.³⁵ The incorporation of As-functionality was achieved by statistical copolymerisation of varying amounts of AsAm in either the PEGA or NIPAM block, whilst keeping the overall chain length of the polymer constant ($DP_n = 100$, Scheme S1).

Initially, a non-As functional control polymer PEGA₂₀-*b*-NIPAm₈₀ was synthesised with homopolymerisation of PEGA in water, complete within 15 mins (>99% conv., $M_{n,SEC} = 11800 \text{ g mol}^{-1}$, $\bar{D} = 1.07$). Addition of a deoxygenated aliquot of NIPAm then furnished the targeted block copolymer PEGA₂₀-*b*-NIPAm₈₀ (**P1**, 98% conv., $M_{n,SEC} = 25400 \text{ g mol}^{-1}$, $\bar{D} = 1.27$, Figure S1). Arsenical monomer, 4-(*N*-acrylamido)phenylarsonic acid (AsAm, ESI), was then incorporated into corona-/core-forming blocks by altering the monomer feed ratio of either the first block (PEGA₂₀-*n*-*co*-AsAm_n, **P2** $n = 3$, **P3** $n = 5$) or the chain extension (NIPAm₈₀-*n*-*co*-AsAm_n, **P4** $n = 5$, **P5** $n = 10$). Successful inclusion of AsAm into the block copolymer was confirmed by ^1H NMR with appearance of aromatic signals of AsAm ($H_{l,m}$, Figure 1) at 7.5–7.7 ppm in addition to the signals corresponding to PEGA ($H_{g,i}$) and NIPAm ($H_{j,k}$). The relative integrals were translated into an experimental polymer composition which confirmed the desired increase in AsAm content as a function of the AsAm monomer feed ratio (Figure S2, Table S1). Block copolymerisation was confirmed by SEC analysis (Figure S3) which showed a shift to higher molecular weight upon chain extension. Increasing the amount of AsAm in either block

appeared to have a detrimental effect on the control of the polymerisation as indicated by deviations in theoretical ($M_{n,th}$) and experimental number average molecular weight ($M_{n,SEC}$) and higher dispersities (**P2–P5**, $\bar{D} = 1.2 - 1.8$) than expected from aqueous SET-LRP polymerisations (Table 1).

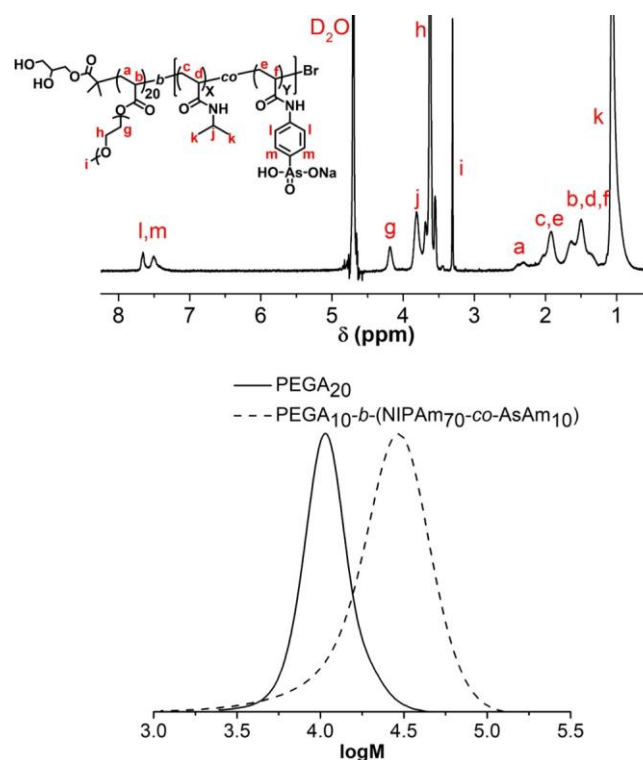


Fig. 1. Representative ^1H NMR (D_2O , top) and SEC (DMF, bottom) confirming the formation of As-functional block copolymers. SEC shows P(PEGA₂₀) $M_{n,th} = 9800 \text{ g mol}^{-1}$, $M_{n,SEC} = 10100 \text{ g mol}^{-1}$, $\bar{D} = 1.16$ (solid) and PEGA₂₀-*b*-(NIPAM₇₀-*co*-AsAm₁₀) (**P5**); $M_{n,th} = 21500 \text{ g mol}^{-1}$, $M_{n,SEC} = 26000 \text{ g mol}^{-1}$, $\bar{D} = 1.19$ (dash).

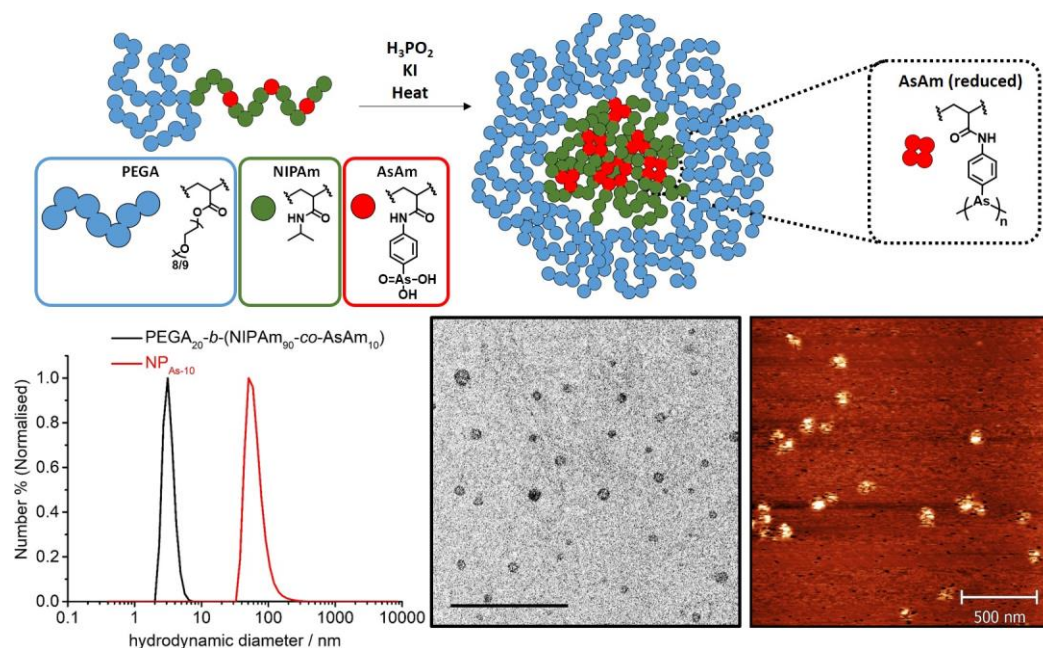


Fig 2. A) Schematic for the simultaneous self-assembly and reductive cross-linking of PEGA₂₀-b-(NIPAm₇₀-co-AsAm₁₀) (**P5**) in H₃PO₂; B) Particle size distribution curves (DLS, 1 mg/ml, H₂O) of PEGA₂₀-b-(NIPAm₇₀-co-AsAm₁₀) **P5** (black) and the corresponding crosslinked nanoparticle **NP_{As-10}** (red); C) TEM image of **NP_{As-10}** (scale bar = 500 nm); D) AFM image of **NP_{As-10}** (scale bar = 500 nm).

The thermoresponsive behaviour and propensity for aggregation for each polymer was investigated by variable temperature dynamic light scattering (DLS) of aqueous solutions of the polymers (1 mg/ml) at 5 °C intervals between 25–60 °C. PNIPAm₈₀ synthesised by aqueous SET-LRP underwent macroscopic precipitation as expected between 35–40 °C (Figure S4), whereas the control block copolymer **P1** formed small aggregates with hydrodynamic diameters (D_h) of 12 – 15 nm at $T > 45$ °C (Figure S5).

Incorporation of AsAm into the corona-forming block also resulted in the formation of nanoparticles the size of which increased as a function of the AsAm monomer feed (**P2**, D_h = 20 nm; **P3**, D_h = 33 nm, Figure S6). However, when AsAm was incorporated into the core-forming NIPAm block (**P4** and **P5**) no self-assembly was observed (D_h = 4 nm, Figure S7). Under the reaction conditions the pendent arsenic acid group of AsAm is ionised (Na⁺ salt) and hydrophilic. It was hypothesised that incorporation into the NIPAm block precluded the expected phase transition. Consequently, the pH of the polymer solutions was measured and found to be 10.3. Acidification of the polymer (**P4**) solution using HCl to close to neutral (pH = 6.6) had little effect resulting in no particle formation (D_h = 8 nm). However, further acidification to pH = 2.5, which is closer to the pK_a of arsenic acid ($pK_{a1} \approx 2$)³⁷ results in protonation of the arsenic acid groups leading to the formation of particles with D_h = 30 nm (Figure S8). In an identical titration, polymers **P2** and **P3** underwent self-assembly across the pH range forming nanoparticles, the sizes of which increased as the pH decreased (pH 10.3 = 48 nm; pH 2.5 = 98 nm, Figure S8).

In pure aqueous solution all the nanoparticles formed from **P1** – **P5** disassembled upon rehydration of the NIPAm block on cooling to 25 °C. Under reducing conditions (aqueous H₃PO₂), the pendent arsenic acid group (As(V)) can undergo reductive

coupling to As(I),¹⁹ with formation of As-As bonds in the form of As_n homocycles. It was hypothesised that reductive coupling could provide a novel approach to crosslinking and stabilisation of the organic arsenical copolymer nanoparticles derived from **P2** – **P5**. The polymers (10 mg/ml) were dissolved in an aqueous solution of H₃PO₂ prior to heating at 60 °C to facilitate both self-assembly and reduction processes. Under these conditions both **P2** and **P3** formed particles with D_h of the order of 40 nm and 80 nm respectively by DLS. However, the presence of the AsAm (n = 3, 5) in the corona-forming block was not sufficient to stabilise the particles formed after heating for 10 – 90 minutes, in line with previous methods employed to achieve reductive coupling.²⁰ Disassembly was observed within 10 minutes upon cooling back to 25 °C (Figure S9). Conversely, when AsAm was confined to the more densely packed core of the particles derived from **P4** (**NP_{As-5}**) and **P5** (**NP_{As-10}**), the particles formed (D_h = 45 nm) upon heating at 60 °C in the presence of H₃PO₂ retained their assembled structure upon cooling for up to 60 minutes, suggesting successful crosslinking through the formation of As-As bonds (Figure S10). The nature of the crosslinking was inferred from IR spectroscopy through disappearance of the As-O signals associated with the pendent arsenic acid (As(V)) moieties (Figure S11). Increasing the amount of AsAm in the monomer feed from **P4** (n = 5) to **P5** (n = 10) resulted in the formation of more stable particles, with **P5** forming stable particles after only 10 minutes of crosslinking, whereas **P4** required at least 30 minutes to form particles that were stable upon cooling to 25 °C (Figure S12).

The particles formed from **P5** (**NP_{As-10}**) exhibited thermoresponsive character, reversibly contracting and swelling upon heating and cooling cycles (Figure S13), in accordance with the transition of the core from a hydrophobic to hydrophilic state respectively. The enhanced stability of

NP_{As-10} was further confirmed following purification and re-dispersion of the crosslinked particles in deionised water (1 mg/ml, Figure S14). Whereas **NP_{As-5}** was shown to disassemble during the purification process (dialysis against deionised water), **NP_{As-10}** retained its self-assembled structure and thermoresponsive properties (Figure S15). Transmission electron microscopy (TEM) and atomic force microscopy (AFM) of **NP_{As-10}** confirmed the formation of nanoparticles with sizes < 100 nm (Figure 2).

Two additional polymers were then synthesised to investigate the effect of AsAm monomer feed on self-assembly and particle stability. Thus, PEGA₂₀-*b*-NIPAm_{80-n}-CO-AsAm_n (**P6**, *n* = 15; **P7**, *n* = 20) were prepared. In line with the previous syntheses both blocks reached high conversion (> 99%), the presence of each monomer was confirmed by ¹H NMR (Figure S16) and successful chain extension was confirmed by SEC analysis (Figure S17). The experimental monomer feed was again confirmed by ¹H NMR (Table S1). This was supported by cryo-probe ¹³C NMR which was performed to quantitatively confirm the AsAm monomer feed ratio present in the block copolymers capable of forming self-assembled nanoparticles (**P4-P7**, Figure S18, Table S2).

Polymers **P6** and **P7** underwent self-assembly in aqueous solution at elevated temperature (60 °C, Figure S19) and were cross-linked via reductive coupling, under the same conditions as **P5**. As expected, the resulting nanoparticles were sufficiently stabilised through reductive coupling to be re-dispersed in water, whereby the stabilised particles (**NP_{As-10}**, **NP_{As-15}**, **NP_{As-20}**) were analysed by DLS (Figure S20), TEM (Figure S21), and AFM (Figure S22). The data obtained for **NP_{As-15}** was in good agreement revealing particle sizes < 50 nm whereas for **NP_{As-20}** DLS and AFM were in good agreement but the TEM revealed much larger particle sizes (≈ 200 nm). However, in the absence of staining with uranyl acetate, TEM of **NP_{As-20}** furnished smaller particles with sizes comparable to those obtained from DLS and AFM (Figure S23). To determine more accurate particle size data (*D_h*, aggregation number - *N_{agg}* and nanoparticle molecular weight - *M_{w,NP}*) static light scattering (SLS) was performed (Figure S24). According to SLS particles **NP_{As-10}** and **NP_{As-15}** were similar, whereas increasing the AsAm monomer feed to *n* = 20 (**NP_{As-20}**) resulted in the

formation of more densely packed particles as indicated by the increase in the *M_{w,NP}* ($1 \times 10^6 - 4 \times 10^6$ g/mol) and *N_{agg}* (62 - 148), which coincided with a decrease in the *D_h* obtained from DLS (43 - 36 nm) (Table S3).

The relative stabilities of **NP_{As-10}**, **NP_{As-15}** and **NP_{As-20}**, were initially investigated in aqueous solution at 37 °C, in which **NP_{As-10}** was found to be stable for 48 hours where **NP_{As-15}** and **NP_{As-20}** remained stable for at least 96 hours (Figure S25). In aqueous glutathione (GSH) at a concentration mimicking intracellular conditions ([GSH] = 5 mM), further differentiation in particle stability was observed. **NP_{As-10}** was stable for only 1 hr with the majority of the nanoparticles undergoing disassembly within 3 hrs. The faster rate of disassembly was mirrored by **NP_{As-15}** and **NP_{As-20}** which disassembled within 12 hrs and 20 hrs respectively (Figure 3). The enhanced rate of disassembly is attributed to the formation of more enthalpically favoured As-S bonds in favour of the weak As-As bonds originally formed through reductive coupling. The trend suggests that particle stability can be tuned by adjusting the AsAm monomer feed which could be advantageous for applications such as drug delivery. Finally, the stability was investigated under aggressive oxidative conditions (aqueous H₂O₂, 5 mM). Under these conditions all nanoparticles were completely disassembled within 1 hr (Figure S26). As the particles were originally crosslinked via reductive coupling, it is likely that disassembly occurs under the strong oxidative conditions in aqueous solution through hydrolysis of the As-As bonds and oxidation of As(II) back to As(V).

Considering the successful synthesis, self-assembly and responsive crosslinking of As-functional block copolymers and with potential biomedical applications in mind, evaluation of their toxicity is essential. It has recently been reported that polymeric arsenicals exhibit limited toxicity *in vitro*.^{17, 18} Here, the acute toxicity of the As-functional block copolymers (**P2-P7**) and the nanoparticles (**NP_{As-10}**, **NP_{As-15}**, **NP_{As-20}**) were determined *in vitro* via a standard XTT assay using the human PC3 cell line as model. PC3 (human prostate carcinoma) cells were obtained from the European Collection of Cell Cultures (ECACC). Pleasingly, it was found that all polymers (**P2-P7**) and their associated nanoparticles (**NP_{As-10}**, **NP_{As-15}**, **NP_{As-20}**) were not toxic at concentrations up to 2.0 mg/ml (Figure S27).

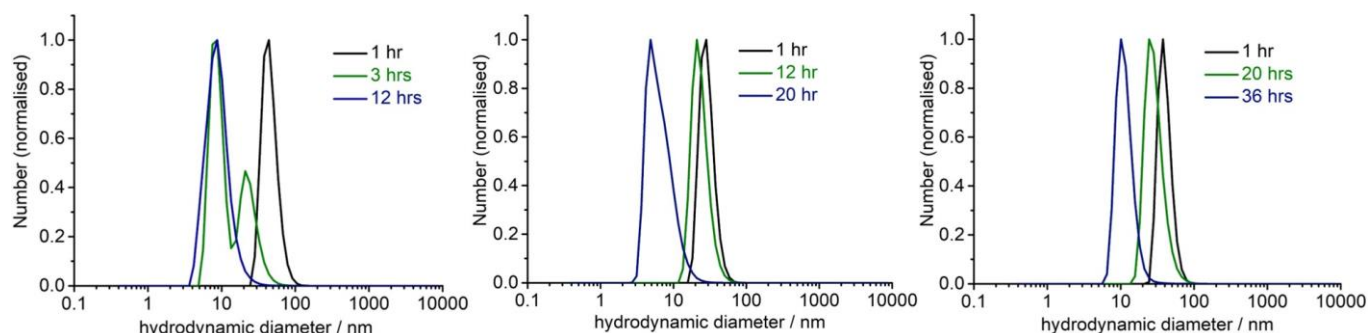


Fig 3. Particle size distribution (DLS), illustrating the relative stability of **NP_{As-10}** (left), **NP_{As-15}** (centre) and **NP_{As-20}** (right) in aqueous GSH (5 mM, 1 mg/ml)

Conclusions

Block copolymers containing an As-functional monomer (AsAm) have been synthesised by aqueous SET-LRP. Various amounts of AsAm have been incorporating into the hydrophilic

corona-forming block ((PEGA_{20-n}-co-AsAm_n)-b-NIPAm₈₀) or the thermoresponsive core-forming block (PEGA₂₀-b-NIPAm_{80-n}-co-AsAm_n). The block copolymers undergo self-assembly at elevated temperatures (60 °C) to form nanoparticles ($D_h < 50$ nm). Reductive coupling of pendent arsenic acid (As(V)) functional groups has been investigated for the first time for crosslinking and stabilisation. The presence of AsAm in the corona forming block ($n = 3, 5$) is insufficient for particle stabilisation upon cooling to ambient temperature. Conversely, incorporation of AsAm ($n = 5, 10, 15, 20$) into the more densely packed core of the nanoparticles affords particles that are stable upon cooling to ambient temperature. The nanoparticles and the polymers they are derived from are non-toxic and the stability of the nanoparticles in aqueous solution and model biological solutions (GSH, H₂O₂) increases as a function of the AsAm monomer feed, both of which we believe could be advantageous of biomedical applications.

Conflicts of interest

There are no conflicts to declare.

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